Application of Orthogonal Array Tests Method to Optimize Operating Conditions for Iron Ore Sintering

Yu-Cheng CHEN,1) Yi-Min SUN,2) Jin-Luh MOU3) and Perng-Jy TSAI1,4)

1) Department of Environmental and Occupational Health, Medical College, National Cheng Kung University, 138, Sheng-Li Road, Tainan 70428, Taiwan. E-mail: pjtsai@mail.ncku.edu.tw 2) Department of Occupational Safety and Health, Chung Hwa University of Medical Technology, 89, Wenhuwa 1st St., Rende Shiang, Tainan 71703, Taiwan. 3) Steel & Aluminum R&D Department, China Steel Corporation, 1 Chung-Kang Road, Siaogang, District, Kaohsiung 81233, Taiwan. 4) Sustainable Environment Research Center, National Cheng Kung University, 1 University Road, Tainan 70101, Taiwan.

(Received on October 14, 2008; accepted on January 6, 2009)

The objective of this study was to determine optimal operation parameters for increasing iron ore sinter productivity (SP) and sinter strength (SS) during sintering process by using the orthogonal array test method, and examine their emissions. Three operating parameters, including the water content (Wc; range=6.0–7.0 mass%), suction pressure (Ps; range=1,000–1,400 mmH2O), and bed height (Hb; range=500–600 mm) were selected for conducting experiments in a pilot-scale sinter pot to simulate various sintering operating conditions of a real scale-sinter plant. We found the resultant optimal combination (Wc=7.0 mass%, Ps=1,400 mmH2O, and Hb=500 mm) could increase SP up to 20.2% in comparison with the current operating condition of a real-scale sinter plant (Wc=6.5 mass%, Ps=1,200 mmH2O, and Hb=550 mm). The results of the ANOVA analysis indicates that Wc and Ps were the two significant parameters (p<0.05) accounting for 50.3% and 36.7% of the total contribution of the three selected parameters, respectively. The SS of the resultant optimal combination shows no significant difference (only increased 2.2%) as compared with the current operating condition of the selected real-scale sinter plant. By examining the emissions of SOx, NOx, and particulate matters, the values obtained from the optimal combination were quite comparable to those of the current operating condition. The above results further confirm the applicability of the obtained optimal combination for the real-scale sinter production.

KEY WORDS: iron ore sintering; productivity; strength; optimal operation parameter; orthogonal array test.

1. Introduction

The iron ore prices which triggered by strong market demands and the decline of high grade iron ore supply have increased drastically during past few years. As a result, low grade iron ore fines are being used increasingly in the sinter plant, which poses an important issue regarding how to enhance sinter productivity (SP) and sinter strength (SS) while using low grade iron ore fines in the sintering process. Moreover, it should be noted that the emission of SOx, NOx, and particulate matters (PM) from the sintering process are strongly affected by the content of iron ore fines and sintering conditions.1,2) Therefore, measures to be taken for enhance SP and SS should consider their side effects on the emissions of SOx, NOx, and PM from the environmental aspect.

SP and SS are affected by many factors such as the properties of raw mixture, bed structure, and operation conditions.3–6) Control of the sintering bed structure is well known to be an efficient method for increasing SP7,8) and SS.9) The advanced granulation process is an important approach to improving pseudo-granulates for promote bed permeability during sinter making process.9) The bed permeability can be also affected by operation conditions such as air flowrate which involved fan’s power, bed cross-sectional area, bed height and suction across the bed.10) As changing the raw mixture properties and bed cross-sectional area and controlling the airflow for increasing SP and SS would be impractical in the real situation, water content (Wc), suction pressure (Ps), and bed height (Hb) become feasible operation parameters to be considered in a real situation without increasing cost of the sinter plant. In other words, the optimal operation conditions might provide a promising solution to increase SP and SS while using low grade iron ore fines.

In principle, experimental design methods can be used to determine the optimal operating condition for a given purpose. For many years, experimental design methods originally developed by Fisher have been widely used in many industries.11) However, the use of the above methods might be subjected to request for a large number of experiments to be carried out as the number of the designed parameters increased. To solve the above problems, the Taguchi experimental design is considered as a less complicated method requiring a much smaller number of experiments to be conducted for identifying an optimal operation condition.
Taguchi experimental design is a powerful tool that provides a simple, efficient and systematic approach to optimize operating conditions under designated ranges of all selected parameters. The method is valuable when the designed parameters are qualitative and discrete. The method can be used to optimize the performance characteristics through the settings of designed parameters and reduce the sensitivity of the system performance to sources of variation. In this study, the Taguchi experimental design is used to determine the optimal operating condition for increasing SP and SS during the sintering process. In addition, the emissions of SOx, NOx, and PM were examined to ensure that the optimal combination obtained from the Taguchi experimental design will not increase its environmental impact.

2. Material and Methods

2.1. The Pilot Scale Sinter Pot and Its Operating Procedures

A pilot scale sinter pot was used in this study to simulate the real-scale sintering process (Fig. 1). This sinter pot included a pot body (inner diameter = 330 mm, height = 600 mm), an ignition hood, and a windbox connected to an exhaust duct. Six kilograms of hearth layer sinter (particle diameters = 10–15 mm, thickness = 40 mm) were placed inside the sinter pot. During sintering, the designated ignition temperature in ignition hood was specified at 1150–1200°C for 1.5 min and then hold in another 1.5 min for keeping heat. During this period (i.e., starting from the ignition to the removal of the ignition hood) the suction pressure inside the sinter pot was controlled at 800 mmH2O by using an electromagnetic valve. After ignition, the suction pressure was raised to 1200 mmH2O and then kept constant throughout the end of the sintering process. The total sintering time was around 35 min depending on the experimental conditions.

The sintering raw mixture used in this study was directly obtained from the real-scale sinter plant. It consisted of the iron ore (52.8 mass%), coke breeze (4.0 mass%), anthracite (1.84 mass%), serpentine (0.42 mass%), marble (1.98 mass%), slurry (0.56 mass%), and return fine (31.5 mass%; including water content (Wc; 6.0–7.0 mass%), suction pressure (Ps; 1000–1400 mmH2O), and bed height (Hb; 500–600 mm) were selected in this study. The selected ranges of the above three parameters were based on the past operating experience of selected sinter plant and the published references.7,14,15 A specific combination of the parameter levels were Wc = 6.5 mass%, Ps = 1200 mmH2O, and Hb = 550 mm, which were served as the reference combination.

Table 2 shows the selected levels for each operation parameter. A L9(34) orthogonal array (with four columns and nine rows) was applied in this study according to the Taguchi experimental design.12 Since the experimental design was orthogonal, it was possible to discriminate the main effect of each individual parameter at each designated level. As shown in Table 2, nine combinations of the three selected operation parameters were chosen for conducting experiments. Subjected to the cost associated with pot test and sampling, each designed experiment combination was repeated twice (n = 2) in this study.

2.2. The Taguchi Experimental Design

The working steps for the Taguchi experimental design include: (1) selection of operation parameters; (2) determination of the number of levels for each selected parameter; (3) selection of the appropriate orthogonal array and arrangement of operation parameters to the orthogonal array; (4) conducting experiments based on the arrangement of the orthogonal array; (5) analysis of the experimental results using the signal-to-noise (S/N) ratio and ANOVA analyses; (6) selection of the optimal combination of levels for the selected operation parameter; and (7) verification of the above optimal combination by conducting a confirmation experiment.12,13

2.3. Selected Experimental Parameters, Levels and Orthogonal Array

Three operation parameters (and their testing ranges), including water content (Wc; 6.0–7.0 mass%), suction pressure (Ps; 1000–1400 mmH2O), and bed height (Hb; 500–600 mm) were selected in this study. The selected ranges of the above three parameters were based on the past operation experience of selected sinter plant and the published references.7,14,15 A specific combination of the parameter levels were Wc = 6.5 mass%, Ps = 1200 mmH2O, and Hb = 550 mm, which were served as the reference combination. Table 2 shows the selected levels for each operation parameter. A L9(34) orthogonal array (with four columns and nine rows) was applied in this study according to the Taguchi experimental design.12 Since the experimental design was orthogonal, it was possible to discriminate the main effect of each individual parameter at each designated level. As shown in Table 2, nine combinations of the three selected operation parameters were chosen for conducting experiments. Subjected to the cost associated with pot test and sampling, each designed experiment combination was repeated twice (n = 2) in this study.

2.4. Evaluation of Sinter Productivity and Sinter Strength

The SP, expressed in tons (t) per square meter (m²) of grate area of sintering machine per day (d), was calculated from the sintering time, the cross-sectional area of the pot grate, and the weight of sinter product recovered from the
test (by deducting the weight of hearth layer). The SS was measured by using a modified ISO 3271 test method.16)

2.5. Air Sampling and Analysis
Because the instability of the airstream occurred during the first 5 min of the sintering process (i.e., the time needed for adjusting the suction pressure to reach the designated level), the flue gas of the first 5 min was not collected. As a result, the sampling time for each flue gas sample was ~30 min. The concentrations of SOx and NOx in the flue gases were analyzed by a digital-direct infra-red gas analyzer (LAN COM 3). PM in the flue gases was sampled isokinetically throughout each batch sintering and collected by a tube-type filter (Whatman-Silica Glass Microfiber Thimble, 25 × 90 mm²). The filters were weighed by a six-digital electronic microbalance after sampling to obtain the particle mass.

2.6. Data Analysis
In the Taguchi experimental design, the term “signal” represents the desirable value (mean) for the output characteristic and the term “noise” represents the undesirable value (standard deviation, S.D.) for the output characteristic. S/N ratios meant to be used as measures of the effect of noise factors on performance characteristics. S/N ratios take into account both amount of variability in the response data and closeness of the average response to target. In this study, the S/N ratio based on the concept of the-higher-the-better was used to characterize SP and SS. The S/N ratio \( h \) was defined as:

\[
h = 10 \log (\text{M.S.D.}) \quad \text{(1)}
\]

Where, mean-square deviation (M.S.D.) was the calculated variance for a characteristic value \( y \). The S/N ratio in decibel (dB) units was used due to the value of 10 times the common log of equation (Eq. (1)) for comparison. The M.S.D. characterized the-higher-the-better obtained as:

\[
\text{M.S.D.} = 1/n \sum_{i=1}^{n} (1/y_i^2) \quad \text{(2)}
\]

Where, \( n \) was number of test, and \( y_i \) was the value of SP and SS obtained from the \( i \)th test. The predicted S/N ratio (or SP and SS) \( (\beta) \) for the optimal combination could be calculated as follows:

\[
\beta = \eta_m + \sum_{i=1}^{o} (\bar{\eta}_i - \eta_m) \quad \text{(3)}
\]

Where, \( \eta_m \) was the total mean S/N ratio, \( \eta_i \) was the maximum S/N ratio (or the minimum SP and SS) obtained from the \( i \)th parameters in their three designated levels, and \( o \) was the number of our selected parameters.

In addition, the analysis of variance (ANOVA) was used to investigate the effect of each individual parameter on SP and SS.

3. Results
3.1. SP, SS and Their S/N Ratio
Table 2 shows the data of the SP and SS obtained from nine designed experimental combinations. The calculated total mean of SP and SS were 30.6 t/m²/d (range = 25.5–35.2 t/m²/d) and 72.0% (range = 70.5–73.3%), respectively. The S/N ratio of the total mean of the SP and SS for each individual parameter in three designated levels according to its orthogonal array experimental combination is also presented in Table 2. The range of the total mean S/N ratio for SP and SS were between 28.1 dB and 30.9 dB (mean = 29.6 dB) and between 37.0 dB and 37.3 dB (mean = 37.2 dB), respectively.

3.2. S/N Ratio Response and ANOVA Analysis
The real value and S/N ratio response at the three selected parameters (including Wc, Ps and Hb) in each of their three designated levels for the SP and SS are showed in Table 3 and Table 4, respectively. For each selected parameter, the difference between maximum S/N ratio and its corresponding minimum S/N ratio (i.e., max–min) represents the effect of the given parameter on determining SP and SS. Based on this, we found that the effects in sequence for the three selected parameters on SP were Wc (1.36 dB), Ps (1.20 dB), Hb (0.400 dB), and that on SS were Ps (0.120 dB), Hb (0.080 dB) and Wc (0.060 dB). Figure 2 shows the trend of the real value for each selected parameter at the three designated levels affecting SP and SS, re-
spectively. For SP, both Wc and Ps shared the same trend in their resultant S/N ratios (i.e., S/N ratio increased with increase of our designed levels). The above trend was different from that of Hb (i.e., S/N ratio increased with increase of our designed levels). Again, the combination of Wc (=6.5 mass%), Ps (=1 200 mmH2O), Hb (=500 mm) were found with the highest S/N ratio for each of the three selected parameters, and hence was considered as the optimal operation condition for increasing SP.

In this study, the ANOVA analysis was used to prioritize effects of the three selected parameters on determining total SP and SS and estimate which designed parameters have a significant effect based on F-test. When F-value is greater than 4, it implies that the designed parameter has a significant effect on study target. In the present study we found that Wc (F-value = 7.33, p = 0.013) and Ps (F-value = 2.16, p = 0.172) were the significant parameters respectively accounting for 50.3% and 36.7% of the total contribution of the three selected parameters to SP (Table 5). Based on the SS result obtained via ANOVA analysis, it can be found that Ps (F-value = 2.16, p = 0.172) is a dominant factor affecting SS accounting for 34.7% of the total contribution. However, significant differences can not be found in these three designed parameters (Table 6).

3.3. Comparison SP and SS between the Reference and the Optimal Combination

Table 7 shows the SP levels, and its S/N ratio obtained from the reference combination (i.e., Wc =6.5 mass%, Ps =1 200 mmH2O, and Hb =550 mm) and the resultant optimal combination (i.e., Wc =7.0 w%, Ps =1 400 mmH2O, and Hb =500 mm). The SP and its corresponding S/N ratio for the reference combination were found as 29.9 t/m2/d and 29.5 dB, respectively. For the optimal combination, its SP and S/N ratio (predicted based on Eq. (3)) were found as 35.9 t/m2/d and 31.2 dB, respectively. The difference in the above two S/N ratios (1.7 dB) indicating that the use of the optimal combination would result in the increase of SP from the sintering process up to 20.1% in comparison with that of the reference combination. For confirmation
Table 7. The real values of SP (t/m²/d) and SS (%), and their corresponding S/N ratio (dB) obtained from the reference operation combination and prediction of optimal operation combination (including both predicted and that obtained from the confirmation experiments).

<table>
<thead>
<tr>
<th>Testing results</th>
<th>Reference operation combination</th>
<th>Optimal operation combination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prediction</td>
<td>Confirmation</td>
</tr>
<tr>
<td>SP</td>
<td>29.9</td>
<td>35.9</td>
</tr>
<tr>
<td>(29.5)</td>
<td>(31.2)</td>
<td>(31.1)</td>
</tr>
<tr>
<td>SS</td>
<td>72.1</td>
<td>73.7</td>
</tr>
<tr>
<td>(37.2)</td>
<td>(37.4)</td>
<td></td>
</tr>
</tbody>
</table>

( ): S/N ratio

Purpose, experiments (n=2) were conducted based on the specification of the resultant optimal combination. The resultant total SP and its corresponding S/N ratio were found as 35.6 t/m²/d and 31.1 dB, respectively. The increase in S/N ratio from the reference ratio to the optimal combination (confirmation experiment) was 1.6 dB, and the resultant decrease in total SP was up to 19.1%. The above results further confirm the applicability of the obtained optimal combination for reducing SP during the sintering process. Simultaneously, the SS has been also estimated using above optimal combination (i.e., Wc=7.0 mass%, Ps=1,400 mmH₂O, and Hb=500 mm). The resultant SS was slightly decreased to 1.8% (fell to the range from 72.3 to 71.0%) in comparison with the reference combination. However, this value obtained from the optimal combination was quite comparable to that of the current criteria (SS>70.0%) in the real world.

Table 7 shows the SS level and S/N ratio obtained from the reference combination and the resultant optimal combination (i.e., Wc=6.5 w%, Ps=1,200 mmH₂O, and Hb=600 mm). The SS and its corresponding S/N ratio for the reference combination were found as 72.1% and 37.2 dB, respectively. For the optimal combination, its sinter strength and S/N ratio were found as 73.7 and 37.4 dB, respectively. The difference in the above two S/N ratios (=0.2 dB) indicating that the use of the optimal combination would result in the increase of SS from the sintering process only up to 2.2% in comparison with the reference combination. The above value had insignificant rising from the reference combination to the resultant optimal combination. Therefore, based on the above reason the confirmed tests of the optimal combination were not repeated for SS.

4. Discussion

As the results shown, the SP significantly increases with rising Wc and Ps in a given parameter at three designed levels and the highest SP S/N ratios were obtained at the highest level of Wc and Ps. The above result was consistent with that found in Kasai et al. and Haga et al. who have indicated that the increase of Wc in raw mixtures could increase the permeability of sintering bed and combustion efficiency (due to the abundant coke breezes and limestone fines coating on the surface of particles), and hence leads to increase SP during sintering processes. Nath et al. have indicated that the high Ps, particularly in 1,300–1,500 mmH₂O, could significantly increase melting time and oxidation activity which results in the increase of SP. The above result was also consistent with that found in Yang et al. The optimal Hb was found at its corresponding lowest level (500 mm) that might be because the lower Hb result in lower pressure drop and higher bed permeability in the sintering bed. However, it was noteworthy that the resultant SS could also be slightly decreased as 6.2% by using above optimal combination (i.e., Wc=7.0 mass%, Ps=1,400 mmH₂O, and Hb=500 mm) to increase SP.

The resultant SS using optimal combination presented insignificant difference as compared with reference combinations. The satisfied SS under the designed boundary of our selected parameters could be approached as using current operation combination (reference combination). Furthermore, the sintering process was complexities and the SS might involve more than effecting factors and hence warrants need for future investigation.

5. Conclusions

This study was conducted optimize operation parameters in the sintering process for increasing SP and SS without increasing emissions of SOx, NOx and PM by using Taguchi experimental design. The SP could be increased significantly up to 20.2% as using optimal combination. Wc and Ps were significant factors to enhance SP in the sintering process, by accounting for 50.3% and 36.7% of the total contribution of the three selected parameters, respectively. However, the SS could not be significantly increased from the reference combination (72.1%) to the resultant optimal combination (73.7%). In addition to the increase of the SP, the concentration of SOx and NOx, also could be decreased based on the determined optimal combination. In this study, the feasible operation parameters and their designed levels were chosen to determine the optimal combination for increasing SP and SS without increasing emissions of SOx, NOx and PM by using Taguchi experimental design. The above results could be further confirmed the applicability of the obtained optimal combination for the real-scale sinter plant.
REFERENCES
